A Closer Look at Nucleosynthesis

According to the Committee on High Energy Density Plasma Physics at the National Academy of Sciences, one of the great challenges facing scientists today is understanding how elements form. This process, called nucleosynthesis, occurs at the extremely high temperatures and pressures found in stars and supernovae—an environment that has been nearly impossible to reproduce in a laboratory setting. When experiments begin on the National Ignition Facility (NIF), scientists will have the tools they need to examine this previously unseen process.

With its 192 laser beams, NIF will generate 2 megajoules of laser energy—enough to create a miniature star. Scientists can use this scaled version of the stellar environment to study how stars create the elements. Livermore researchers are collaborating with colleagues at the University of California at Berkeley, Lawrence Berkeley National Laboratory, the Colorado School of Mines, and Ohio University to prepare for the initial NIF experiments.

Three Stellar Processes

Apart from hydrogen, helium, and a small amount of lithium, which formed during the first three minutes after the big bang, most of the elements in stars are created in one of three nucleosynthesis reactions. Nuclear fusion creates the elements in a young star. Two neutron-capture reactions, called the slow (s) and rapid (r) processes, kick in as a star ages and dies, forming most of the elements heavier than iron.

In the fusion reaction, nuclei of lightweight elements slam together and fuse, releasing large amounts of energy and generating the nuclei of heavier elements. Lightweight elements, which have the fewest protons, appear near the top of the periodic table. For instance, nuclei of hydrogen—the lightest element, with one proton—can fuse to form helium. Helium nuclei can in turn create carbon. Carbon becomes part of the fuel for producing even heavier elements, such as oxygen.

Because both nuclei carry a positive charge, they cannot fuse unless they overcome the Coulomb repulsion—an electrostatic force that tends to separate them and prevent interaction. "We can demonstrate a similar effect by trying to force two magnets together," says Livermore nuclear physicist Lee Bernstein. "We can feel the magnets repel each other, and the closer we push them, the stronger that force becomes." In the dense interiors of stars, an effect called electron screening reduces the positive charge of two nuclei. Electron screening thus increases the probability that the nuclei will overcome the Coulomb repulsion and fuse to create a new element.

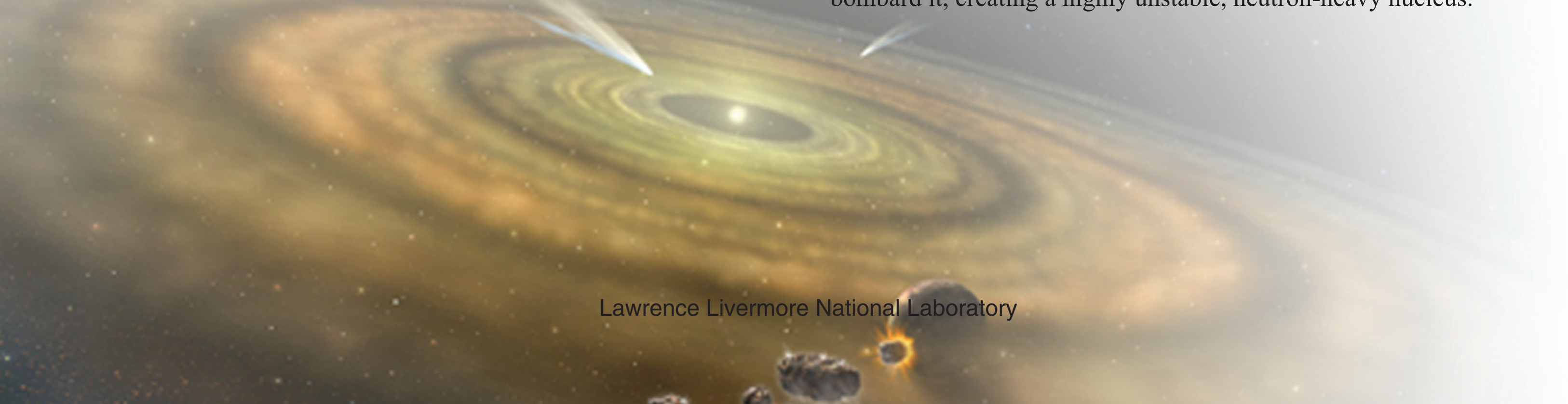
To date, accelerators are the only technology that can duplicate this process. With an accelerator, researchers can bombard a target with a very high-energy pulse of positively charged ions. However, even if an accelerator could be tuned to the low energies relevant to stellar temperatures, the probability of an ion fusing with the nucleus of a target atom is extremely low. The particle fluxes generated by the accelerator would be too low to produce enough reactions to be measured. "Running an accelerator continuously might yield two such reactions in a month," says Livermore physicist Dick Fortner.

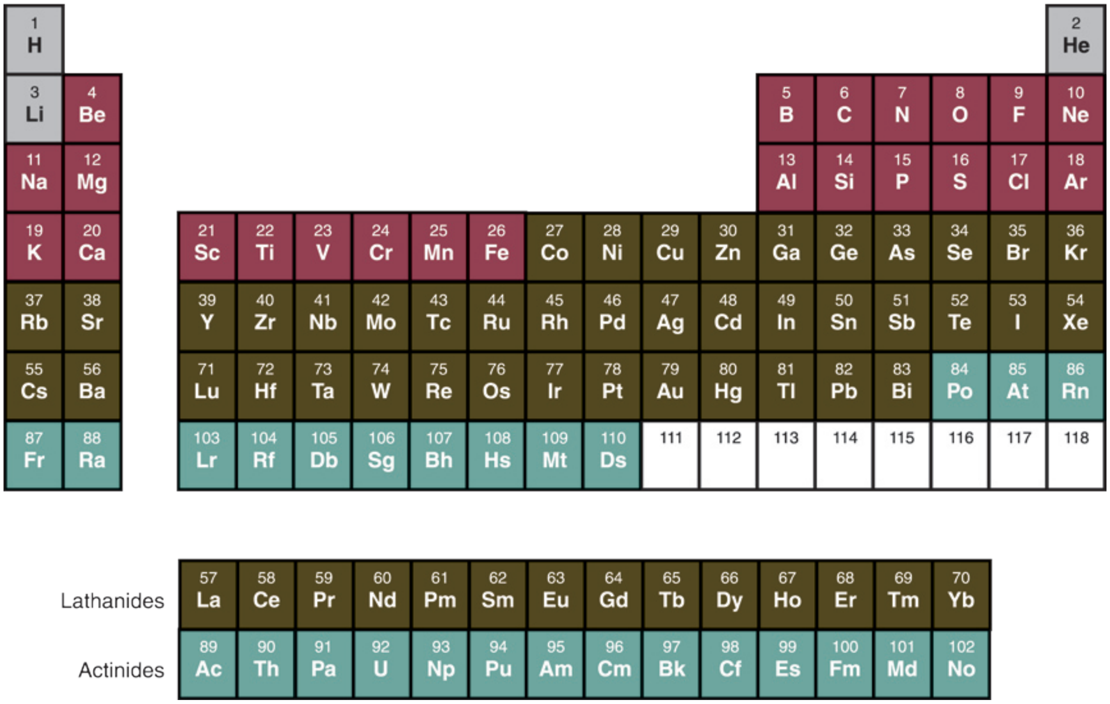
NIF will provide the experimental conditions needed to observe these elusive reactions. It will create a starlike thermal environment with densities between 10^{23} and 10^{26} atoms per cubic centimeter and temperatures up to 10 kiloelectronvolts. These experiments will use target capsules loaded with a fuel of helium-3 and helium-4. NIF's laser beams will compress the fuel and produce beryllium-7, a critical reaction in stellar hydrogen burning, at a rate that can be measured for the first time. "We estimate that one experiment will produce 300,000 beryllium-7 atoms," says Bernstein.

From Lightweight to Heavyweight

The s-process occurs at relatively low neutron densities and intermediate stellar temperatures. In this process, a nucleus captures a neutron. The resulting nucleus can be stable, or if it is radioactive, it will decay to a stable form before the next neutron is captured. The s-process accounts for about half of the isotopes of elements heavier than iron. Because the s-process involves stable isotopes with long decay times, scientists can readily examine it in the laboratory. As a result, these physical reactions are well understood.

The r-process, in contrast, occurs only when neutron densities and temperatures are extremely high, such as those in a supernova when a star collapses and explodes. In the r-process, neutrons hit a nucleus, and before the nucleus can decay, even more neutrons bombard it, creating a highly unstable, neutron-heavy nucleus.





The periodic table lists elements according to the number of protons in their nucleus. Thus, it begins with the element that has the fewest protons—hydrogen, with one—and proceeds to the element known to have the most, which currently is element 118, with 118 protons. (See *S&TR*, April 2007, pp. 22–24.) Gray elements formed in the first three minutes of the big bang. Other lightweight elements (burgundy) form in fusion reactions that create heavier elements, which serve as fuel for even heavier elements. Slow neutron capture, called the s-process, occurs in massive stars to form elements beyond iron (brown). Still heavier elements (turquoise) form in explosive environments, such as in a supernova, through a rapid neutron-capture reaction called the r-process.

The number of additional neutrons eventually reaches equilibrium so that their capture and release occur at about the same rate. At this point, when a neutron-capture reaction emits a photon, the photon knocks a neutron from the nucleus. This equilibrium point is typically about 20 neutrons beyond the neutron-rich edge of the stable nuclei.

This equilibrium point occurs when the nucleus reaches a neutron closed-shell state. This state is similar to the closed shells of electrons in noble gas. Just as an atom of noble gas is chemically inactive and cannot interact with additional electrons, a neutron closed-shell nucleus has difficulty interacting with additional neutrons. Before the nucleus can capture another neutron, it must undergo beta decay, in which a neutron converts into a proton. The nucleus can now capture another neutron—an action that results in another neutron closed-shell nucleus, which also must decay before yet another neutron can be captured. This process may continue through several decay-and-capture cycles until a nucleus has the right number of protons and neutrons and can once again capture multiple neutrons.

Neutron closed-shell nuclei are referred to as r-process waiting-point nuclei. Once the nuclei can again capture multiple neutrons, they proceed along the path of many neutron captures and occasional beta decays. Eventually, they accumulate enough neutrons to reach the next neutron closed shell and the next set of waiting-point nuclei.

Because the flow of nuclei stalls at these points, waiting-point nuclei are the most abundant ones in the r-process. When the high neutron density of the r-process ends, these nuclei undergo a series of beta decays that ultimately produce the abundance peaks characterizing the r-process nuclei.

Unfortunately, accelerators cannot create nuclei so far from stability, which prevents scientists from studying waiting-point nuclei in the laboratory. However, some NIF experiments will produce extremely high neutron fluxes (about 10^{33} to 10^{34} neutrons per square centimeter per second) within about 10^{-10} second—all in a controlled laboratory environment. This short burn time will allow researchers to study the neutron-rich nuclei created in the r-process. The resulting data will help improve the accuracy of models that simulate the brief, violent life of an exploding star.

Measuring the Mysteries of Stars

"Because of NIF, we're on the edge of an exciting time in nuclear science," says Bernstein. "We will be able to explore realms of nuclear physics that have been off limits to laboratory experiments. NIF will shine a light, so to speak, on two areas of the periodic table that have been dark for a long time."

—Ann Parker

Key Words: Coulomb repulsion, elements, fusion, hydrogen burning, National Ignition Facility (NIF), nucleosynthesis, periodic table, rapid (r) process, slow (s) process, stellar evolution, waiting-point nuclei.

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